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TITLE: STATIC PERFORMANCE OF A PULSEJET USING ETHYLENE OXIDE AS A FUEL IN BOTH LIQUID AND DECOMPOSED GASEOUS FORMS

AUTHOR: D. S. Perkins

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DIVISION OF FAIRCHILD ENGINE AND AIRPLANE CORPORATION

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MODEL NO.

CONTRACT NO. AF 33(600)-5860 Supplement No. 5 - Item 1.2

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1. SUMMARY

Static tests have been conducted with a 6.75 inch diameter pulsejet engine using ethylene oxide (ETO) as a fuel. The ETO was injected as a liquid, both pure and mixed 1:1 with gasoline. It was also decomposed in a gas generator and the gaseous products of decomposition were injected downstream parallel to the engine axis: (1) through holes drilled in two tubes mounted between the valve box and engine, and (2) from a single nozzle. The decomposed ETO was also injected radially. The only method that resulted in satisfactory engine operation was the first of the two axial injection configurations.

The only advantage of using ethylene oxide as a pulsejet fuel as observed during sea level static testing was its ease of starting.

The peak thrust and specific fuel consumption of the configurations tested is summarized below.

	FUEL	PEAK THRUST, lb.	SFC lbs. fuel per hr. lb thrust
1.	Gasoline (interior baffled fuel nozzle)	52	3.3
2.	1:1 gasoline and liquid ETO (by volume)	53	5
3.	Liquid E.T.O.	28	10
4.	Decomposed ETO - Axial injection through #54 holes	46	15
5.	Decomposed ETO - Radial injection through #54 holes	Started but would not continue running	----
6.	Decomposed ETO - Laval nozzle (mono-propellant rocket thrust only)	3.8 (non-burning)	102
7.	Decomposed ETO - Laval nozzle without pulsejet shell (mono-propellant rocket thrust)	14 (non-burning)	28

2. INTRODUCTION

An investigation of the performance of ethylene oxide as a fuel, in liquid form as the sole fuel and also mixed with gasoline, and as gaseous decomposition products from a rocket type gas generator, was conducted under the thrust augmentation provisions of Supplement 5 of Exhibit "A" of Contract No. AF 33(600)-5860. Ethylene oxide differs from the fuels commonly used in a pulsejet engine mainly because it can be used as either a bi-propellant or a mono-propellant. In the latter case it decomposes into a mixture of gases when heated to a temperature of 1060°F. In this form it is used a a mono-propellant rocket fuel. However, these gaseous decomposition produc will burn when mixed with air. It is on this latter basis as a gaseous bi-propellant that "ram-rocket" operation has been predicted by other investigators. An interesting adjunct to this study of ethylene oxide as a pulsejet fuel is consideration of a "pulse-rocket" jet propulsion system, also intended to burn the gaseous decomposition products.

The entire ethylene oxide fuel system including control panel, fuel tanks, and gas generator was furnished by the Turbo Engineering Department of the American Machine and Foundry Company. Technical assistance was also provided for operation of the fuel system throughout the testing phase of the program.

3. TEST EQUIPMENT

1 - 6.75" engine, No. M102

3 - 6.75" valve boxes

1 - Axial injection fuel ring

1 - Radial injection fuel ring

1 - Delaval nozzle

1 - Spark plug, .06" gap

1 - 3.8" dia. venturi

1 - Standard fuel system with 20 gph fuel nozzle and baffle

1 - E.T.O. gas generator

2 - E.T.O. service tanks and valves

1 - E.T.O. supply tank

1 - E.T.O. control panel

1 - Nitrogen pressurization tank

4. INSTRUMENTATION

Atmospheric Pressure: Mercury barometer

Atmospheric Temperature: Mercury thermometer

Atmospheric Humidity: Sling psychrometer

Fuel flow: liquid: Fisher-Porter "Flowmeter" Serial No. 111-1480/2 ±1% accuracy

Fuel flow: gas: Calibrated orifice and pressure gage

Frequency: Audio oscillator

Thrust: Hagen null balance Thrustorq meter, calibrated 4-16-54

Shell Temperature: "Tempilstik" heat sensitive crayons.

5. TEST SYSTEM OPERATION

The test setup for controlling the decomposition and flow of E.T.O. consisted of a control panel with pressure gages and remote operating valves, two E.T.O. tanks, gas generator and a nitrogen pressurizing tank. Figure 2 shows the essential components of the system. The E.T.O. tank is loaded through the appropriate valve and then pressurized from the nitrogen bottle to the desired value through the pressure regulating valve. The generator is then "armed", i.e., the generator heater is energized for 3 to 5 minutes to bring the critical surfaces of the generator to a temperature sufficient to insure decomposition of the E.T.O. when it reaches the generator. Fuel flow is controlled by remotely operated solenoid valves and is measured by a calibrated metering orifice. After leaving the generator, the now gaseous fuel enters a manifold from which the engine connections were made.

The E.T.O. tank held fuel for about 5 minutes of running after which the pressurizing tank was shut off and the E.T.O. tank vented to atmosphere and refilled.

6. ETHYLENE OXIDE

6.1 Properties

Ethylene oxide is a cyclic ether (C_2H_4O). It is a colorless liquid that freezes at -169°F and boils at 51°F. Some properties of the pure compound in both the liquid and vapor states are given in Table I. E.T.O. is a very volatile liquid with a specific gravity of 0.87. It burns like gasoline as a liquid and also when decomposed and mixed with adequate air. Storage of the liquid in an aircraft or in supply tanks requires pressurized vessels since it has a vapor pressure of 85 psig at 160°F. Further details as to the properties, storage and handling of E.T.O. are presented in the referenced literature from which Figure 3 and Table II are extracted.

6.2 Decomposition

Under certain conditions of temperature and pressure, a controlled decomposition of E.T.O. may be maintained in a device such as the E.T.O. gas generator used in these tests. The liquid is injected into a small steel chamber that contains a heating element that is energized several minutes before firing to provide a temperature sufficient to ensure decomposition. Once started, the exothermic reaction of decomposition maintains itself without further heating. The reaction by chemical analysis is as follows:

$$C_2H_4O \rightarrow .92CO + .79CH_4 + .23H_2 + .09C_2H_4 + .02CO_2 + .02O_2 + .09C + 870 \text{ BTU}$$

Subsequent burning of the combustible mixture will yield an additional 10,830 BTU/pound. The liquid and decomposed E.T.O. burn similarly to liquid gasoline and gasoline vapor, respectively.

7. DISCUSSION OF RESULTS

7.1 Performance with Gasoline

For purposes of comparison a typical static engine performance curve is shown in Figure 4 for an engine burning gasoline. Fuel flow varies from 75pph to 180pph from lean blowout to rich blowout with a peak thrust of 52 pounds and a specific fuel consumption of about 3.3 at peak thrust.

The engine (Figure 1) and fuel injection system for this gasoline test run were the same as used for the liquid E.T.O. and 1/2 gasoline, 1/2 E.T.O. test runs.

7.2 Liquid E.T.O.

Liquid E.T.O. was used as a fue in the same configuration as was used with gasoline. Peak thrust was only about 50% of the gasoline peak thrust with a corresponding specific fuel consumption of about 10. It was inferior in performance, therefore, as compared to gasoline both for thrust and specific fuel consumption. The fuel flow range was from 35 pph to 360 pph.

7.3 E.T.O. Gasoline Mixture (1:1 By Volume)

E.T.O. and gasoline were mixed in the E.T.O. service tanks in a ratio of 1:1. This mixture was then burned as a pulsejet fuel in the same engine and fuel system configuration as the gasoline test run. Peak thrust was 53 pounds which is essentially the same as obtained with gasoline but the specific fuel consumption at peak thrust was about 5 compared to 3.3 for gasoline. The fuel flow range varied from 100 pph to 290 pph.

7.4 E.T.O. Decomposed (Gaseous Products of Decomposition)

7.4.1 Axial Fuel Injection

The E.T.O. decomposition products were burned in the same engine as above but with a different fuel injection system. Fuel was injected into the combustion chamber by means of an axial fuel injection system that consisted of a modified gasoline fuel ring. The nozzle, baffle and supporting fuel tube were removed from a gasoline fuel ring (Figure 8) and two 1/4" O.D. x .035" steel tubes were added with 10 #54 holes drilled on the downstream side of the tubes (Figure 5). The engine started very easily with only a momentary blast of starting air. Peak thrust obtained was about 40 pounds which was apparently near rich blowout, although the limit of flow available from the test setup was reached and a definite maximum fuel flow was not established. The fuel flow ranged from 385 pph at lean blowout to a maximum obtainable flow of 535 pph. Specific fuel consumption was 15 at 40 pounds of thrust.

7.4.2 Radial Injection

Another modified gasoline fuel ring was used to provide radial injection of the decomposed E.T.O. A 6.75" fuel ring was drilled with 16 No. 54 holes around the inside of the ring (Figure 6). This system provided momentary starting but would not continue to run. The E.T.O. gases could be seen escaping forward through the valves, so that it was probable that combustion air, that must enter through the valves, was being restricted by the large volume of injected E.T.O. gases.

7.4.3 Rocket (De Laval) Nozzle

A third and final fuel injection configuration (Figure 7) was tried during performance testing of the gaseous products of the E.T.O. gas generator. A De Laval nozzle was installed so as to expel the gases aft on the engine centerline in an attempt to utilize any available thrust from the rocket nozzle in addition to the basic pulsejet thrust. This is analogous to the basic idea behind the "ram-rocket" configuration. No starts were achieved with this system. It appeared that the jet of hot gases was not spreading and filling the combustion chamber, but was escaping out the tailpipe without forming a combustible mixture with air. It seemed likely that if the hot gases impinged on a baffle located downstream of the rocket nozzle, adequate mixing with air might occur; however, this would practically eliminate the thrust of the rocket nozzle and thus defeat the purpose for using the rocket nozzle. Since only 3.8 pounds of non-burning thrust were obtained with this configuration (giving an sfc of about 102) it was not considered practicable to develop the engine to operate with this system. The thrust of the rocket nozzle when outside the pulsejet shell was 14 pounds (giving an sfc of about 28). The difference in thrusts must be due to internal drag between the rocket jet and the pulsejet shell.

7.5 Operating Temperatures

In general, the pulsejet operation with E.T.O. as a fuel resulted in engine shell temperatures of about 1900°F, which is 200 to 300°F higher than encountered with gasoline fuel. One effect of the hotter engine was to accentuate the decrease in thrust at constant fuel flow when an engine is warming up to operating temperature, that has been observed to a lesser extent with gasoline. The scatter of data shown in Figure 4 for the decomposed E.T.O. is due in part to the above effect.

7.6 Leakage Problem

Leakage of the hot gases that leave the gas generator at high temperature (1700°F) and pressure (1000 psig) required constant re-tightening of fittings after each run. A very small leak in a screwed connection got progressively worse, apparently due to erosion of the fitting. Close tolerance screw fittings or welded connections would be necessary to insure trouble free operation of this fuel system piping.

7.7 Generator Surging

Directly associated with gas leaks was a form of instability of the generator known as "chugging" or surging. If the pressure at the generator inlet was too low or if the outlet pressure was too low, the flow through the generator would start to surge at a low frequency (about one cycle per second) but at high amplitudes. During the second day of testing the above difficulty caused failure of the nuts securing the head of the generator to the chamber (Figure 9). A subsequent stainless steel generator gave satisfactory service throughout the subsequent test, although "chugging" was not entirely eliminated. Leaks in the generator lines were corrected as far as could be ascertained but generator surge persisted. Slight variation in the properties of the delivered E.T.O. was thought to be a possible source of the difficulty.

7.8 Valve Box Life

Valve box life was shortened due to the higher engine and combustion temperatures that resulted from using E.T.O. The engine was not run long enough to determine valve life under steady operating conditions, but it was obvious that the valves were being damaged by heat in a few minutes of running time. The burning was partly due to the fuel injection location being 1/4" aft of the reeds which allowed the combustion to start at the venturi with resulting high temperatures occuring 2 to 3 inches forward of a station that would be normal for gasoline. Engine temperature when running on the decomposition products was measured with a "Tempilstik" crayon and showed a value of 1900°F over nearly the entire engine which is several hundred degrees higher than normal test stand operation with gasoline. The high temperatures were not restricted to parts of the tailpipe, transition, and combustion chamber as with gasoline, but appeared to spread uniformally over most of the engine.

7.9 Engine Frequency

All of the test runs burning E.T.O., both liquid and gaseous, provided frequency data that revealed an engine resonant frequency ranging from 23% to 52% higher than its resonant frequency when burning gasoline. The natural frequency of the valves was about 190 cycles per second and the average recorded engine frequency was about 170 cycles per second, with a resulting ratio of natural frequency to average forcing frequency of 1:1.12.

7.10 System Weight

The weight of the test stand components for the E.T.O. tests was about 600 pounds which includes the nitrogen pressurizing tank and the E.T.O. supply tank but does not include fuel. An estimate for the weight that might be expected for a flying version of the fuel system would be 112 pounds. At 600 pounds per hour per engine for 40 pounds of thrust, 1200 pounds of E.T.O. would be required for a one hour flight. About 1300 pounds of fuel and fuel system would be required therefore, for a two-engined single-place aircraft to fly one hour.

8. CONCLUSIONS

Sea level static testing has shown ethylene oxide to be inferior to gasoline as a pulsejet fuel with respect to thrust, specific fuel consumption, system complexity, fuel handling, and system weight. Ease of engine starting was observed during this program to exceed performance with gasoline.

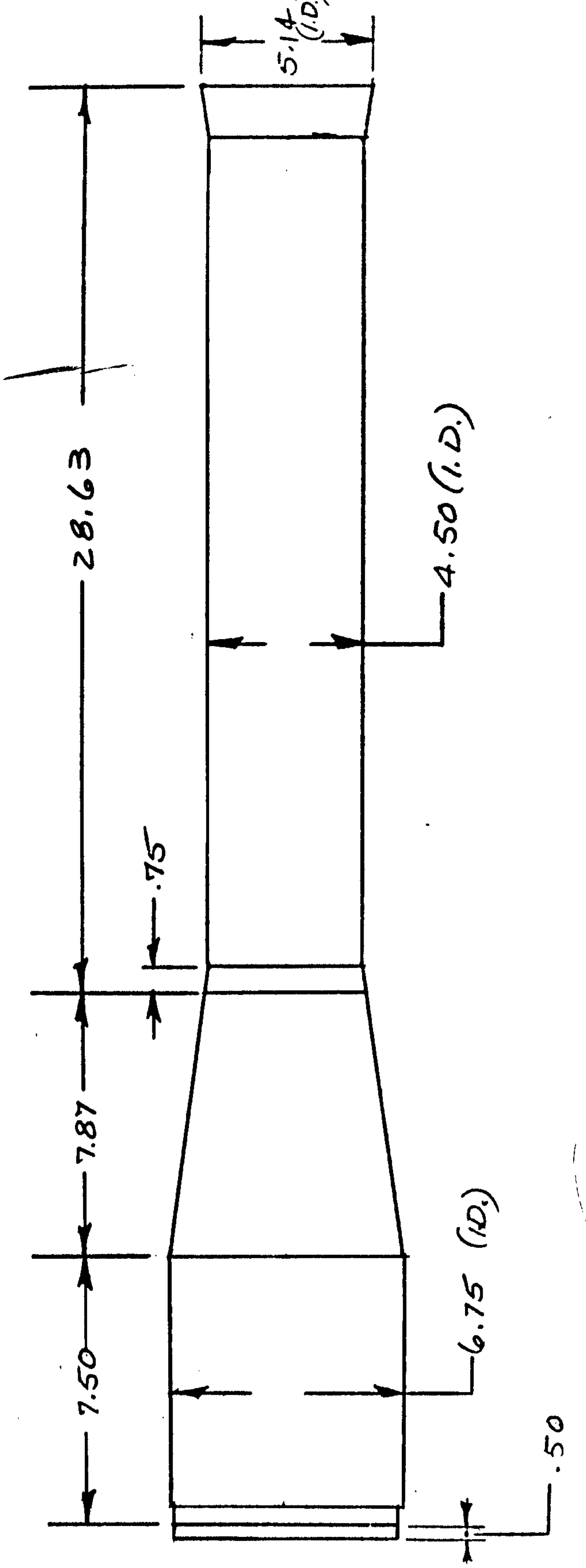
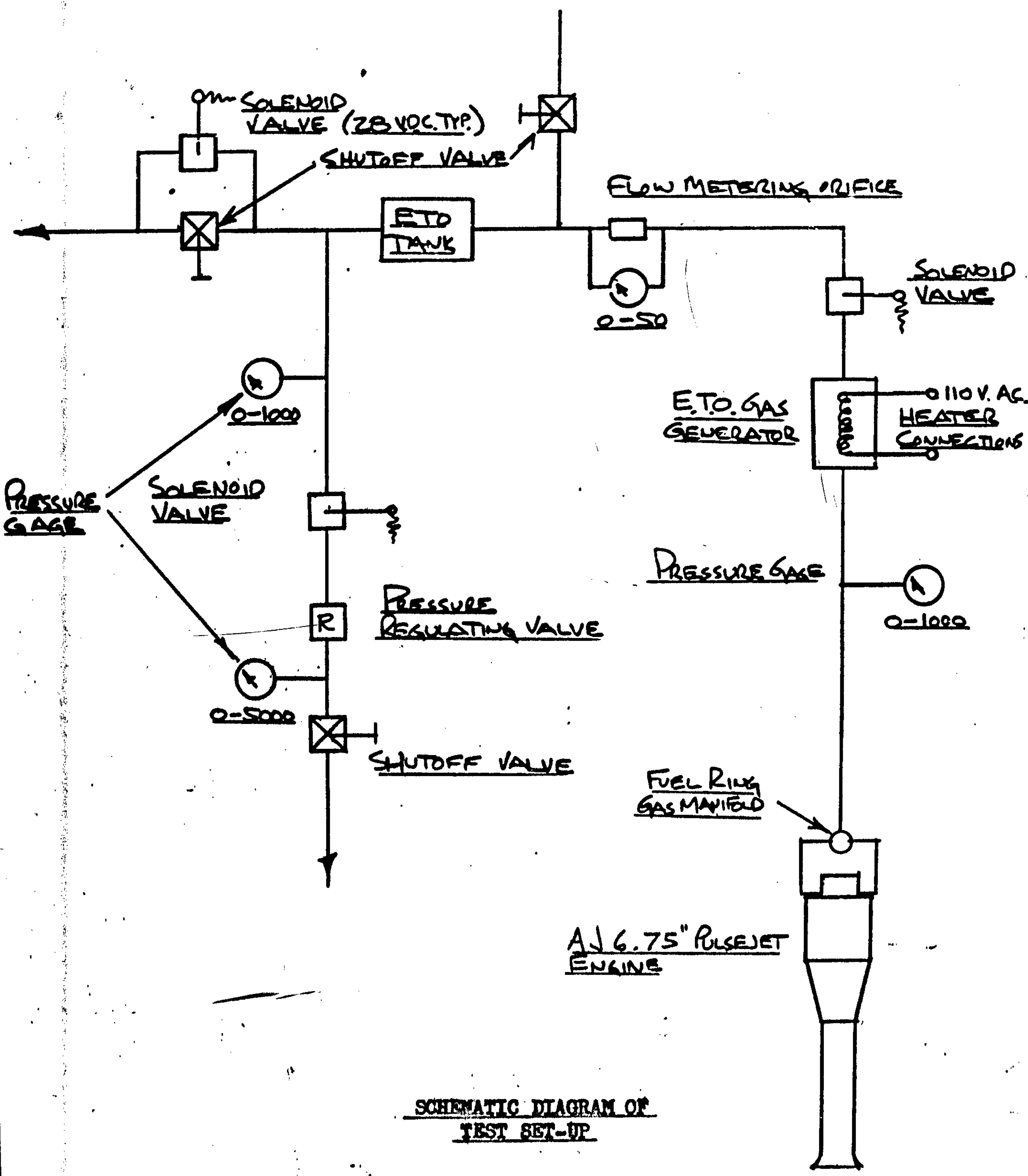


FIGURE I

BASIC DIMENSIONS OF ENGINE USED FOR
ETHYLENE OXIDE TEST PROGRAM

FIGURE 2



SCHEMATIC DIAGRAM OF TEST SET-UP

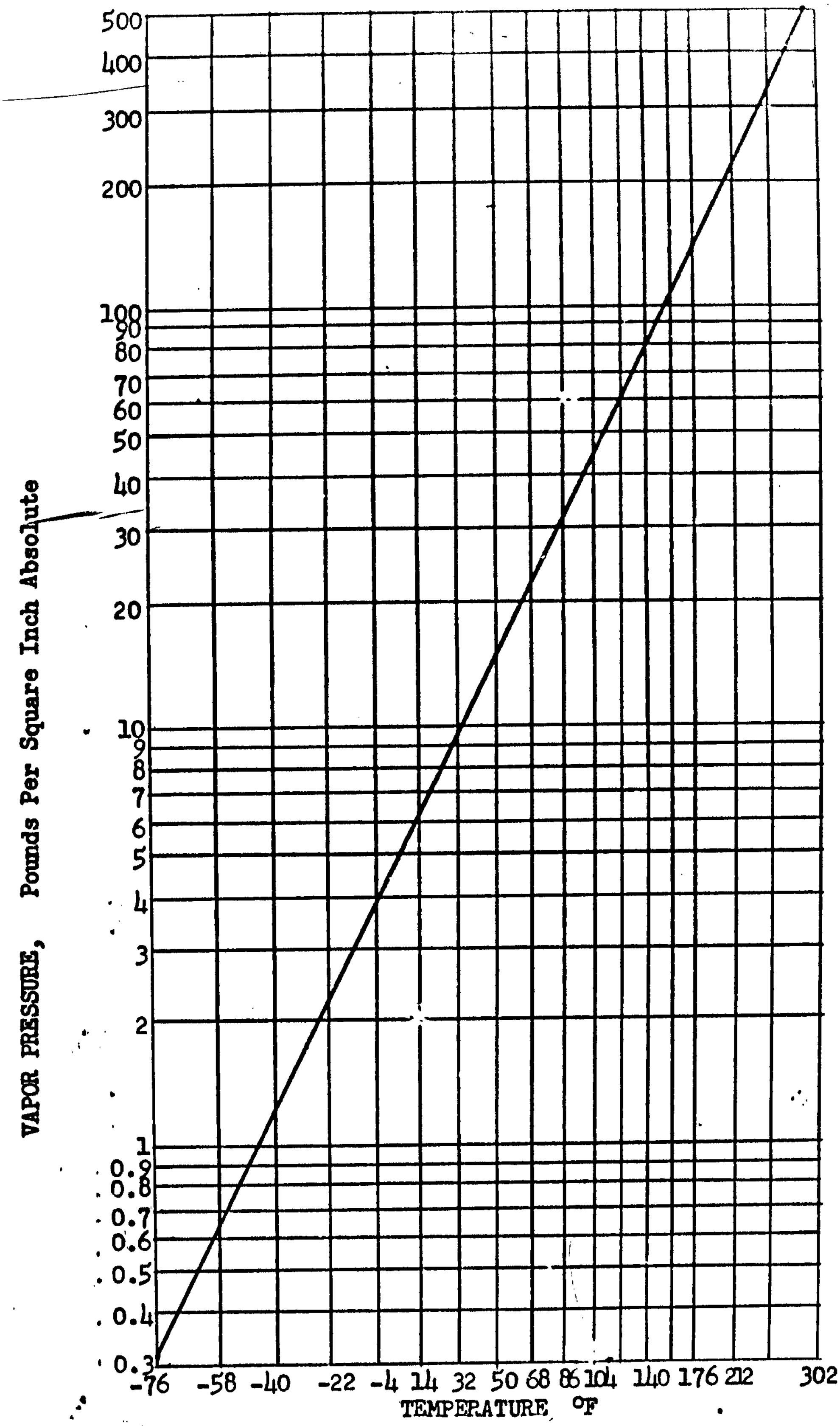


Figure 3 VAPOR PRESSURE OF ETHYLENE OXIDE

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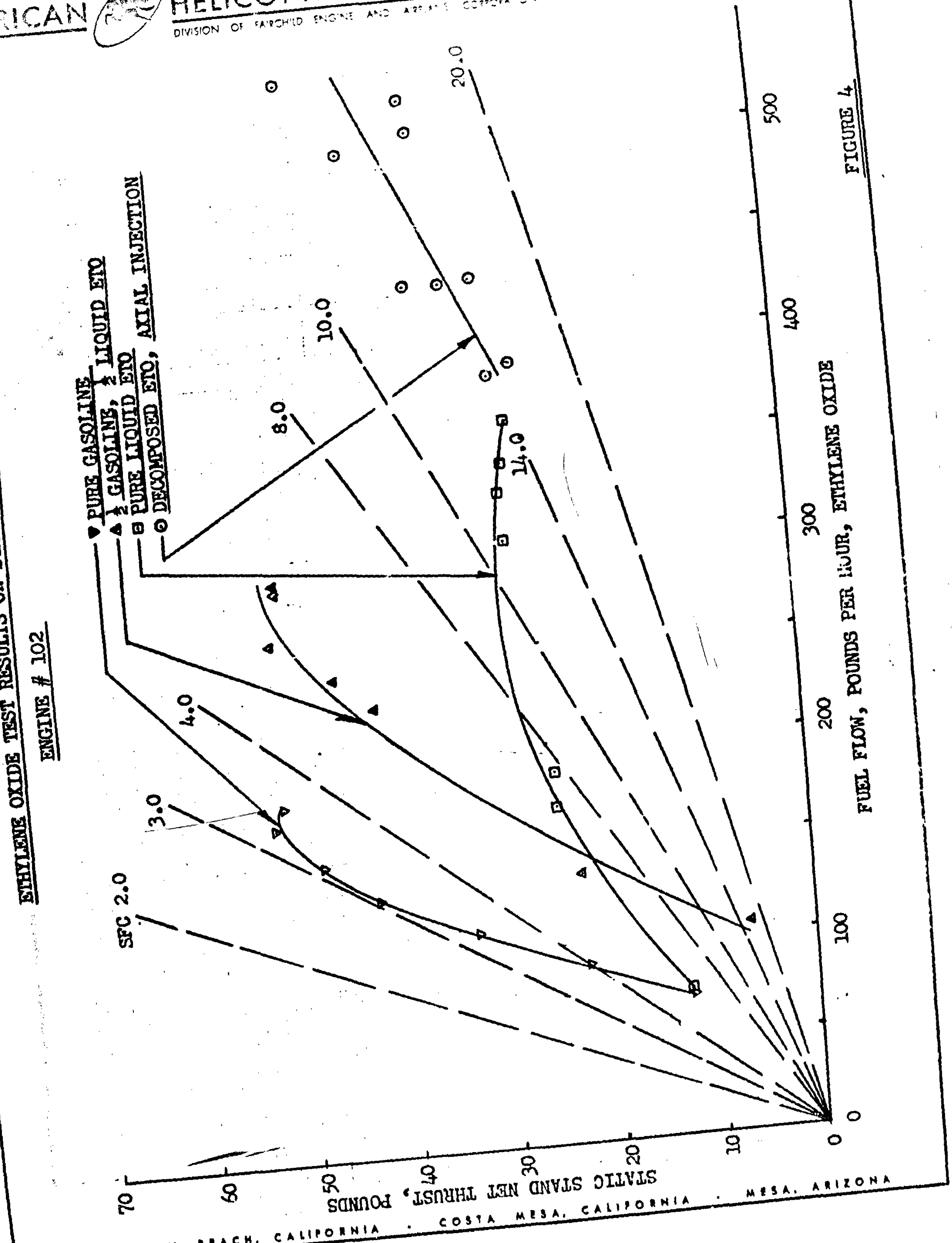

FIGURE 4

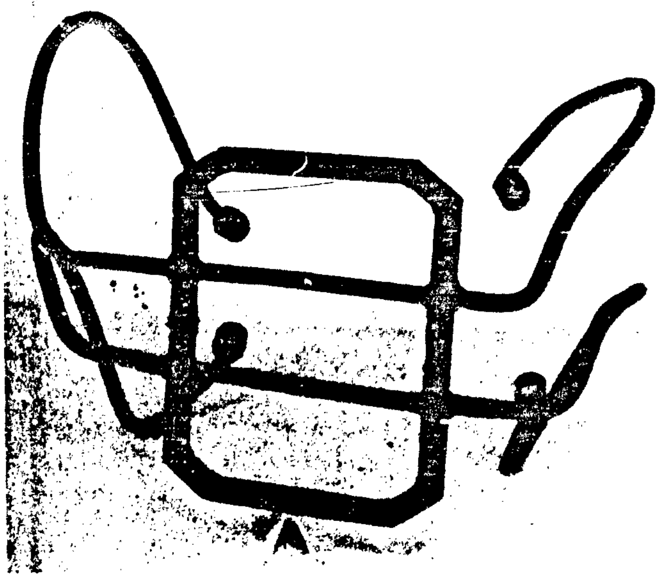

FIGURE 5.

ETO FUEL RING FOR AXIAL INJECTION. RING IS INSTALLED SO THAT HOLES FACE DOWNSTREAM.

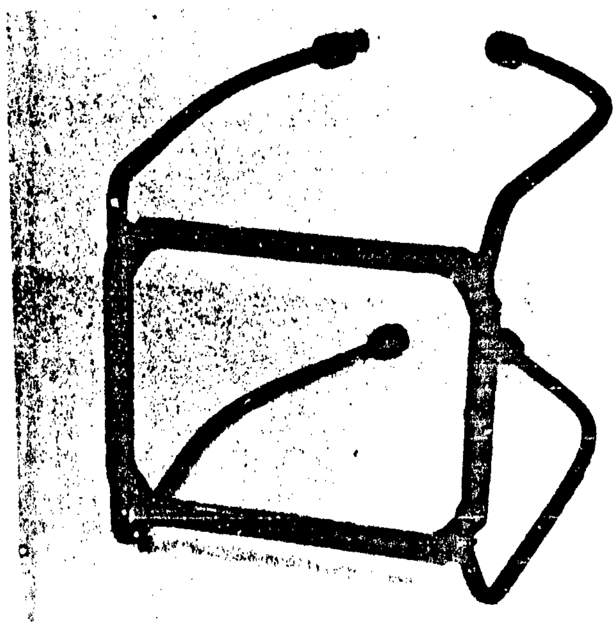

FIGURE 6.

ETO FUEL RING FOR RADIAL INJECTION. NO PULSEJET OPERATION WAS ACHIEVED WITH THIS SYSTEM.

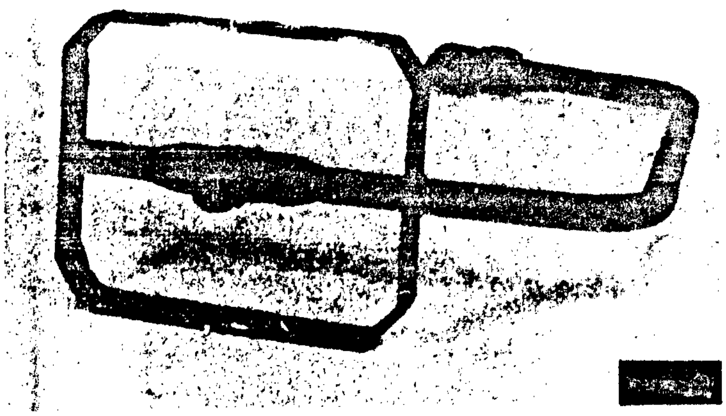

FIGURE 7.

ETO FUEL RING FOR INJECTING ETO DECOMPOSITION GASES. THE RING WAS INSTALLED WITH THE LAVAL NOZZLE (NOT SHOWN) FACING DOWNSTREAM. NO PULSE-JET OPERATION WAS ACHIEVED WITH THIS SYSTEM.

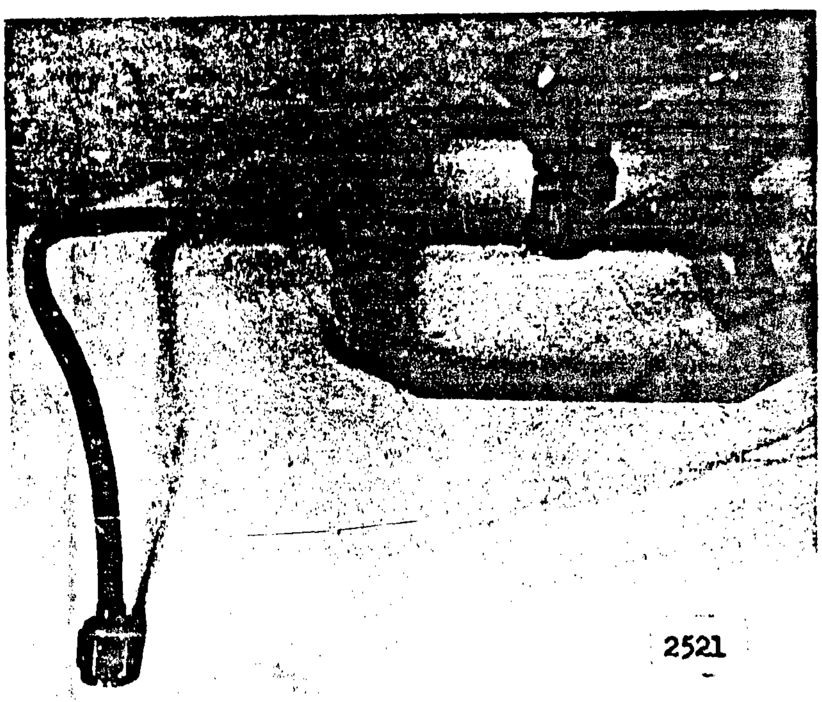

FIGURE 8.

ETO FUEL RING FOR INJECTING GASOLINE, GASOLINE AND LIQUID ETO, AND LIQUID ETO. THE RING WAS INSTALLED WITH THE NOZZLE FACING DOWNSTREAM.

2521

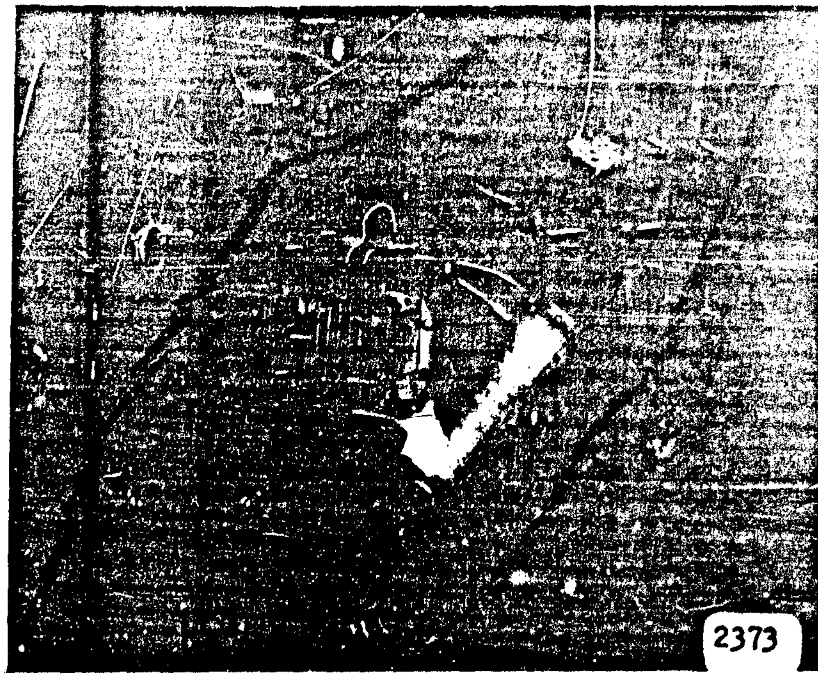

FIGURE 9.

ENGINE ON TEST STAND WITH ETO MANIFOLD ATTACHED, SHOWING BROKEN CONNECTION RESULTING FROM EXPLOSIVE FAILURE OF ETO GAS GENERATOR.

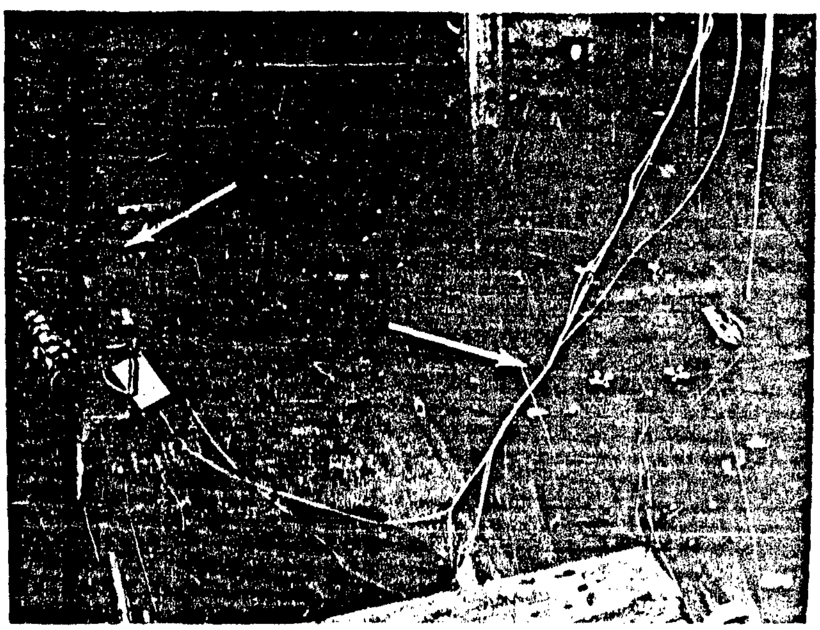

FIGURE 10.

ETO GAS GENERATOR ON TEST STAND (LEFT) AND ETO SERVICE TANKS AND PLUMBING (RIGHT).

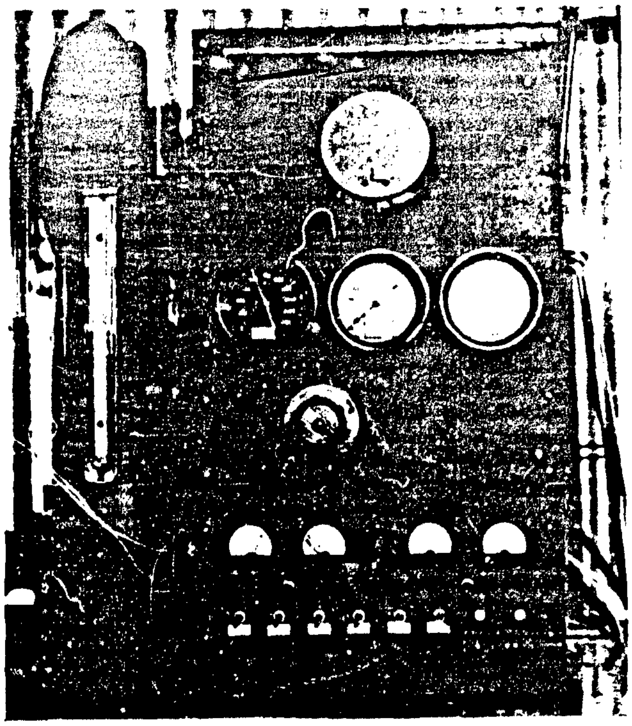

FIGURE 11.

ETO FUEL FLOW AND PRESSURE REGULATING PANEL. THE INSTRUMENTS TO THE LEFT ARE NOT PART OF THE SYSTEM.

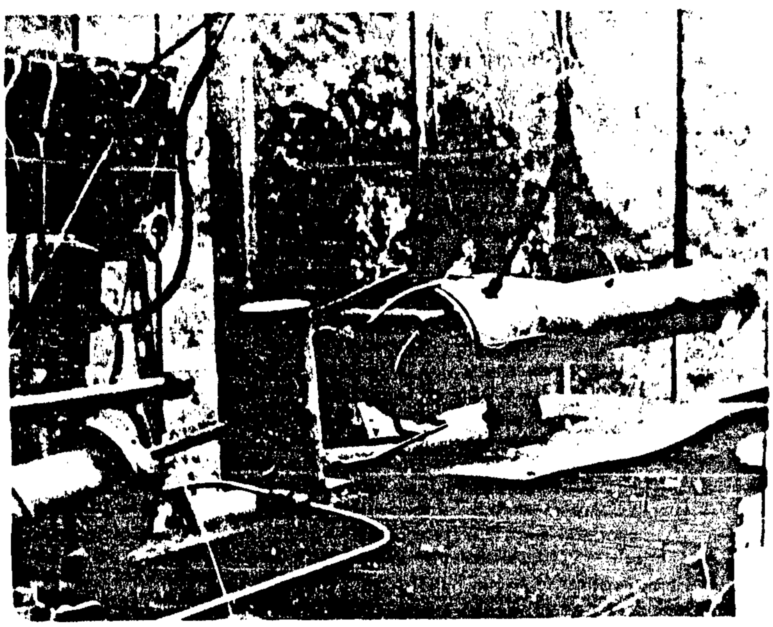

FIGURE 12.

ETO TEST SETUP SHOWING GAS GENERATOR, MANIFOLD, AND TEST ENGINE, IN ORDER FROM THE LEFT. THE FOUR 1/4" O.D. TUBES CONNECT THE MANIFOLD TO THE FUEL RING,

TABLE I

SOME PROPERTIES OF ETHYLENE OXIDE

LIQUID -

Apparent Specific Gravity, 20/20° C.	0.8711
Wt. per gal. at 20°C.	7.249 lb.
Coefficient of Expansion at 20°C.	0.00161
Water Solubility	Complete
Heat of Vaporization at 1 atm	245 Btu per lb.
Flash Point, open or closed cup	less than 0°F.

VAPOR -

Critical Temperature.	195.8°C.
Critical Pressure, abs.	1,043 lb. per sq. in.
Ignition Temperature in air at 1 atm.	429°C.
Decomposition Temperature of pure vapor at 1 atm.	571°C.
Heat of combustion of gas, gross.	308.7 kg-cal. per gm. mol.
Heat of Decomposition of gas	20.0 kg-cal. per gm. mol.

HANDLING CARE -

The principles governing safe handling of Ethylene Oxide arise from the facts that (1) it is a flammable liquid easily ignited, (2) its vapor will decompose violently when exposed to certain temperatures and pressures, and (3) it is toxic and therefore its vapor is not to be inhaled, and (4) it is very reactive chemically.

TABLE II

TEST DATA

	FUEL FLOW W_f, lb/hr.	THRUST lbs.	COMB.CH.PRESS psig	FREQ. cycles/sec	ENGINE TEMP, °F
AXIAL FUEL INJECTION	(non-burning)	.7	---	---	---
	382	27.6	.7	---	1900
	504	33.5	.65	190	1900
	497	40.4	---	---	---
	533	46	---	---	---
	430	35	---	---	---
	389	25.7	---	---	---
	431	28.6	---	---	---
	521	33.9	---	---	---
	410 (non-burning)	.94	---	---	---
LIQUID ETO	171	24.6	---	---	---
	302	27.5	---	---	1800
	187	24.6	---	---	---
	324	27.8	---	---	1800
	342	27.2	---	---	1800
	360	26.6	1.0	164	---
	36(LBO)	6.5	.17	---	---
	.72	12.9	.45	154	---
ETO GASOLINE	95(LBO)	---	---	---	---
	105	6.4	.3	---	---
	135	22.2	1.0	---	---
	225	41.5	1.95	---	---
	240	45	2.15	---	---
	285	52.5	2.6	---	---
	300(RBO)	---	---	---	---
	260	53.6	2.45	---	---
	288(RBO)	52.5	2.45	---	---
ROCKET NOZZLE	389(non-burning)	3.8	negative at least .2psig	---	---